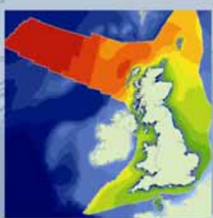
Beatrice Offshore Windfarm Ltd

Beatrice Offshore Wind Farm: Numerical Model Calibration and Validation Report

Report R.1860

January 2012

Creating sustainable solutions for the marine environment


Beatrice Offshore Windfarm Ltd

Beatrice Offshore Wind Farm: Numerical Model Calibration and Validation Report

Date: January 2012

Project Ref: R/3888/9

Report No: R.1860

Version	Details of Change	Authorised By	Date
1	Draft for comment	D Lambkin	19.12.2011
2	Final	D Lambkin	30.01.12

Document Authorisation		Signature	Date
Project Manager:	D O Lambkin		30.01.12
Quality Manager:	C L Hinton		30.01.12
Project Director:	W S Cooper		30.01.12

ABP Marine Environmental Research Ltd
Suite B, Waterside House
Town Quay
SOUTHAMPTON
Hampshire
SO14 2AQ

Tel: +44(0)23 8071 1840
Fax: +44(0)23 8071 1841
Web: www.abpmer.co.uk
Email: enquiries@abpmer.co.uk

ABPmer is certified by:

Summary

This report details the calibration and validation of a set of numerical models of tides and waves covering the region of the Moray Firth, Scotland. These models have been constructed to inform the physical processes assessments of the Beatrice Offshore Wind Farm located in the vicinity of Smith Bank. Following a highly detailed assessment the tide and wave models demonstrate good performance. Model performance with regard to sediment mobility is considered specifically by comparing bed shear stresses from the model with those derived empirically from the field. In this case, the model proves that it is capable of reproducing the frequency and duration of the empirically derived forces applied to the bed by the tides. The particle tracking model is discussed briefly but is not subject to a detailed analysis due to the lack of evidence against which to prove the model. Finally, a critical summary of the models is presented. This concludes that the models are fit for purpose and makes recommendations for the models application.

Beatrice Offshore Wind Farm:
Numerical Model Calibration and Validation Report

Contents

Appendices

Tables

Figures

1. Introduction

The model suite used in this study is MIKE21FM provided by the Danish Hydraulic Institute (DHI). MIKE21FM is capable of modelling in both 2D (depth-averaged) and 3D (depth-resolved) mode as required. It comprises various modules enabling the simultaneous modelling of water levels, currents, waves and sediments if required. This software has been used extensively in similar offshore wind farm investigations, both in the UK and elsewhere in Europe.

Three modules of the MIKE21FM model have been applied here in 2D to resolve the key physical processes (tides and waves) over both the near-field (array scale) and far-field (regional scale). Another module (particle tracking) has been used to model sediment plume dispersion and deposition.

The model design and application and the specification of data input required, follow the best practice guidance outlined in COWRIE 2009. It is noted that there are no widely adopted industry standards defining model calibration and validation. Therefore, ABPmer maintains its own guidelines for the calibration and validation of numerical models (ABPmer, 2011). These guidelines incorporate elements of the SEPA (2009) text which provides general guidelines for model calibration and validation.

2. Modelling Input Resources

2.1 Site Swath Bathymetry Survey

Site specific swath bathymetry has been collected for the application site by Osiris in 2010. Swath bathymetry collected by the MCA (Maritime and Coastguard Agency) has been appended to the application site's specific data. This ensures that a suitable portion of the Moray Firth is captured in high detail for inclusion in the numerical models. The coverage of these data sets is shown in Figure 1.

2.2 Metocean Data from the Site, Collected 2010

Partrac has undertaken an on-site metocean survey for Beatrice Offshore Wind Limited. The first deployment began in February 2010 and consisted of:

- two bed frames located at opposite ends of the application site; and
- a wave buoy located at the north eastern end of the application site.

The bed frame data have been analysed to provide current speeds and directions throughout the water column, water level and wave parameters. Although both bed frames were recovered 15th June 2010, the wave buoy remains in situ.

The spatial and temporal extent of collected data was specified by ABPmer in order to inform and support robust numerical modelling as described here.

2.3 NCEP Winds (1980 to present)

Hindcast winds for the North Sea region and the North East Atlantic have been extracted from the freely-available NOAA NCEP models and applied as the wind field over the wave model numerical domain. These modelled winds provide the driving boundary of the wave model.

2.4 DHI Global Harmonic Tidal Constituents

The DHI modelling software provides the means to predict harmonic water levels for any period of time based upon the satellite derived KMS tidal harmonic database. This is utilised to provide the water level variations that provide the offshore boundary conditions for the tidal model.

2.5 BODC Current Data

The British Oceanographic Data Centre provides a number of data sets free of charge. Following quality checks, these data provides a means of assessing model performance over a wider spatial extent than is otherwise available from the site-specific metocean deployments.

2.6 Tidecalc and Admiralty Chart Tidal Diamonds

Admiralty tidal predictions provide some limited information about the tidal streams in the Firth. These data provide an opportunity to make further comparisons with model output.

3. Mesh Construction

Two separate model domains form the basis of the tide and wave models. The spatial extent of these domains is shown in Figure 2. The extent of the tidal model is determined by the location of tidal amphidromes and the performance of the harmonic boundaries. The wave model extent is determined by the relevant fetch lengths over which winds can generate waves. For both models, the resolution in the vicinity of the application site is of the order of 200m while further offshore the resolution lowers to as much as 40 kilometres. This variable resolution approach ensures that the numerical models are able to adequately capture the features of the high resolution inshore bathymetry surveys.

Each model domain (tide and wave) is based upon the same bathymetry data, which include:

- Etopo2 (far-field areas);
- MCA swath bathymetry (near-field areas); and
- Osiris swath bathymetry of the immediate application site.

The sediment dispersion model is based upon a regular grid not a mesh. However, this regular grid is created by extracting directly from the tidal model mesh. This extraction is of 500m resolution and includes the whole Moray Firth.

4. Tidal Model

4.1 General Design and Setup

The swath bathymetry data was incorporated into the model by amalgamating the three survey data sets. Following adjustments to reference these data to mean sea level, the data were gridded at a suitable resolution for the MIKE21FM modelling software. The boundaries of the tidal model are then driven by harmonically derived water levels using DHI's KMS global tidal harmonic database.

The hydrodynamic model uses a standardised approach to the flooding and drying of inter-tidal areas. For the purposes of the numerical scheme, a model element is classed as 'dry', and excluded from the computation, when the water depth in that cell becomes 0.005m or less. As the water level rises, the element 'floods' and is again incorporated in the computation when the water depth reaches 0.05m.

For the assessment of array-scale (near-field) processes, the foundation structures are represented in the model using the sub grid-scale 'pier resistance' function. In this approach, the resistance to the flow attributable to the presence of sub-grid scale structures (e.g. turbine foundations) is modelled by transforming the drag force on the structure into an equivalent bed shear stress. This is an established approach recommended as best practice (ETSU, 2002). Using this approach the model was run over a spring-neap cycle, thus covering a wide range of tidal conditions.

4.2 Tidal Model Calibration

The first point of discussion is the data collected from the field to which the models are compared. The AWAC devices return vertical profiles of current speed and direction. The models applied here are depth averaged (2D). To facilitate the comparison, the vertical bins of current speed and direction from the field data are reduced to an average representative of the total water column. Additionally, it is known that the levels of backscatter in the vertical data are quite low. This is a result of the naturally low levels of particulate matter in the water. Low backscatter reduces the overall accuracy of the returned data. Every attempt has been made to treat the data appropriately to ignore data returned with that low accuracy. However, the point at which the data is determined from reduced backscatter is not a clearly defined threshold. As a result, some inaccuracy in the field data may remain. This must be considered when the model is compared with the field data.

In order to obtain the best agreement between the model predictions and the records from the site specific metocean surveys, bed roughness was adjusted to fine-tune the model. In this process, agreement was assessed visually and through the use of correlation analyses.

A graphical comparison of the model water level performance at the two AWAC deployment sites (Figure 1) is shown in Figure 3 and Figure 4. The statistical description of the model's performance is detailed in Table 1. Here, negative values indicate under prediction while positive values indicate over prediction. In addition, Figure 5 to Figure 8 show regression plots of water depth, tidal current speeds and tidal current directions for both deployment sites. Figure 6 and Figure 8 also show polar plots of current speed and direction as well as a comparison of current speed envelopes for both field records and model performance.

Table 1. Calibration statistical analysis, water level

Parameter	2a	3a
Mean High Water WL difference (modelled - observed) (m)	-0.06	-0.06
Mean Low Water WL difference (modelled - observed) (m)	-0.01	-0.01
Standard deviation of High Water WL difference (m)	0.08	0.10
Standard deviation of Low Water WL difference (m)	0.07	0.12
Mean High Water phase difference (mins)	7.53	10.04
Mean Low Water phase difference (mins)	12.21	15.40
Standard deviation of High Water phase difference (mins)	8.76	11.28
Standard deviation of Low Water phase difference (mins)	7.18	8.07
High water difference relative to tidal range (%)	-2.67	-2.76
Low water difference relative to tidal range (%)	-0.24	-0.56

Comparing the model against the field measurements, the mean difference in High Water and Low Water is less than 0.07m. The maximum error in High Water levels is found at site 3a where 99% of the data falls within 0.4m of the field data records. A positive phase difference indicates that the model is delayed in time (late) relative to observed values. Phase differences at all deployment sites are around 7 to 15 minutes. The overall consistency in the phase errors and the small standard deviations (approximately 10 minutes) relative to the total phase lag suggest that the model is correctly reproducing hydrodynamic processes at these sites. It is noteworthy that the model reproduces the high-low-high pattern in both the High and Low Water levels as identified in the field records (Figure 3 and Figure 4).

Mean peak ebb and peak flood current speeds are compared in Table 2. The model slightly over predicts peak currents by no more than 0.06m/s. On average current direction errors are of the order of 9° and around 90% of the data fall within ±20°. The model reproduces well the tidal axis at both the 2a and 3a deployment sites (Figure 1) with an error of no more than 5°. It is noted that the field data suggest the tidal axis is not totally rectalinear, i.e. the direction of the flood currents are not directly opposite to the direction of the ebb currents (cf. Figure 6 and Figure 8). However, the misalignment is small and not considered to have any consequence with regards to understanding of in-situ processes. It must be noted that the accuracy of the field data may be less than the accuracy to which the differences between it and the model are quoted.

Table 2. Calibration statistical analysis, current speed and direction

Parameter	2a	3a
Mean speed difference, peak ebb (modelled - observed) (m/s)	0.01	0.02
Mean speed difference, peak flood (modelled - observed) (m/s)	0.03	0.02
Standard deviation of peak ebb speed difference (m/s)	0.06	0.06
Standard deviation of peak flood speed difference (m/s)	0.04	0.04
Mean direction difference, peak ebb (°)	-2.46	3.76
Mean direction difference, peak flood (°)	-8.60	-1.20

Parameter	2a	3a
Standard deviation of ebb direction difference (mins)	2.51	3.96
Standard deviation of flood direction difference (mins)	3.45	4.63
Mean difference relative to max observed speed, peak ebb (%)	2.32	4.54
Mean difference relative to max observed speed, peak flood (%)	4.43	3.88

4.3 Tidal Model Validation

The model was validated throughout the model domain area to indicate satisfactory performance beyond the area of immediate interest. Validation was achieved by comparing the model's performance with field data which was independent of the data used during calibration. The process of validation does not permit the adjustment of the model setup parameters to achieve good performance as it is intended as an independent check on the model's performance. This is undertaken for both water levels and for currents. Model water level output is plotted against Tidecalc predicted water levels for Wick Harbour in Table 3.

Table 3. Validation statistical analysis, water level

Level	Wick
Mean High Water WL difference (modelled - observed) (m)	-0.03
Mean Low Water WL difference (modelled - observed) (m)	0.03
Standard deviation of High Water WL difference (m)	0.06
Standard deviation of Low Water WL difference (m)	0.08
Mean High Water phase difference (mins)	22.3
Mean Low Water phase difference (mins)	38.0
Standard deviation of High Water phase difference (mins)	14.07
Standard deviation of Low Water phase difference (mins)	15.59
High water difference relative to tidal range (%)	-1.60
Low water difference relative to tidal range (%)	1.71

Mean water level differences at both High Water and Low Water are in the order of ±0.03m. it is therefore considered that there is good agreement between the model and Tidecalc predictions . Mean phase differences between the High and Low Waters of the model and those of Tidecalc are around 22 and 38 minutes, respectively. This is most likely attributable to the coarse resolution of the model in the vicinity of Wick Harbour and the complexities of the tidal wave's passage in this embayment. This is deemed acceptable on the basis that water levels perform very well and high model resolution is not required in this location due to its remoteness from the application site.

When comparing the model to BODC field data from the wider region, modelled mean current speeds are generally within 0.07m/s of those recorded in the field. The locations of various BODC data are shown in Figure 9, which also shows the envelopes of current speed for both field and model data. Table 4 details the validation statistics for the corresponding locations shown in Figure 9.

Table 4. Validation statistical analysis, current speed and direction

BODC site identifier	b0012443	b0012479	b0012615	b0014161	b0014185	b0015810	b0016192
Mean speed difference, peak ebb (modelled - observed) (m/s)	-0.05	-0.11	-0.12	0.06	0.05	-0.01	-0.09
Mean speed difference, peak flood (modelled - observed) (m/s)	0.04	0.04	0.13	-0.02	-0.04	0.00	-0.07
Standard dev of peak ebb speed difference (m/s)	0.10	0.08	0.05	0.09	0.11	0.09	0.03
Standard dev of peak flood speed difference (m/s)	0.16	0.14	0.08	0.08	0.07	0.06	0.05
Mean direction difference, peak ebb (°)	-21.23	2.41	10.10	0.39	0.72	3.65	8.92
Mean direction difference, peak flood (°)	-9.79	16.70	125.91	1.67	8.99	-3.18	18.87
Standard dev of ebb direction difference (°)	2.23	3.66	2.11	8.21	8.92	19.74	24.33
Standard dev of flood direction difference (°)	3.99	60.44	91.52	3.42	6.87	6.05	23.80
Mean difference relative to max observed speed, peak ebb (%)	-5.70	-13.79	-23.57	13.43	12.34	-1.52	-27.52
Mean difference relative to max observed speed, peak flood (%)	5.11	5.63	42.12	-2.96	-6.57	1.13	-23.48
BODC site identifier	b0020756	b0020800	b0020928	b0020953	b0020990	b0025865	b0025890
Mean speed difference, peak ebb (modelled - observed) (m/s)	0.12	0.01	0.04	-0.04	0.03	0.03	0.06
Mean speed difference, peak flood (modelled - observed) (m/s)	0.09	-0.02	0.03	-0.03	-0.07	-0.01	0.03
Standard dev of peak ebb speed difference (m/s)	0.08	0.08	0.08	0.02	0.08	0.08	0.08
Standard dev of peak flood speed difference (m/s)	0.05	0.05	0.04	0.03	0.04	0.05	0.05
Mean direction difference, peak ebb (°)	4.20	0.42	-19.78	-2.74	-7.59	-6.87	22.78
Mean direction difference, peak flood (°)	-3.60	4.26	-19.63	115.53	-3.38	17.24	-19.79
Standard dev of ebb direction difference (°)	5.33	6.43	3.20	45.17	10.99	31.50	20.37
Standard dev of flood direction difference (°)	5.31	4.56	3.75	176.76	4.79	6.95	3.83
Mean difference relative to max observed speed, peak ebb (%)	35.33	1.06	10.42	-14.86	6.84	4.28	11.76
Mean difference relative to max observed speed, peak flood (%)	25.45	-3.65	6.65	-10.17	-15.00	-2.01	5.72
BODC site identifier	b0026506	b0047050	b0049161	b0049197	b0049799	b0062034	b0433415
Mean speed difference, peak ebb (modelled - observed) (m/s)	-0.04	0.05	-0.49	-0.05	0.04	0.11	-0.24
Mean speed difference, peak flood (modelled - observed) (m/s)	0.03	0.08	-0.28	0.08	0.02	0.08	0.05
Standard dev of peak ebb speed difference (m/s)	0.10	0.03	0.23	0.09	0.11	0.07	0.04
Standard dev of peak flood speed difference (m/s)	0.08	0.03	0.21	0.09	0.10	0.05	0.07
Mean direction difference, peak ebb (°)	-19.94	7.09	-0.08	8.92	-3.56	-9.17	-2.50
Mean direction difference, peak flood (°)	15.49	9.45	-3.88	-23.90	5.05	8.75	83.11
Standard dev of ebb direction difference (°)	5.02	5.43	2.24	1.93	1.73	3.77	3.18
Standard dev of flood direction difference (°)	6.63	48.98	3.40	12.18	1.42	5.77	69.05
Mean difference relative to max observed speed, peak ebb (%)	-6.38	37.88	-30.21	-6.87	11.97	32.37	-42.87
Mean difference relative to max observed speed, peak flood (%)	8.65	57.58	-21.32	13.03	5.67	22.56	22.78

When comparing the model current speeds and directions with those of the BODC data it must be noted that the BODC data are values recorded at a specific height in the water column while the model returns depth averaged values. Therefore, some differences can be expected due to this difference which must be considered when the comparison is made.

The visual comparison of the modelled currents against the BODC field currents in Figure 9 suggests a good correlation of both current speed and direction. It is noted that although the field data have undergone harmonic analysis to remove meteorological effects, these data are obtained at specific depths in the water column and are therefore may not always representative of the depth-average current speed from the model. Two sites are identified where the model does not fully represent the BODC field data. These sites have BODC labels b0433415 and b0012615 in Figure 9 and are located adjacent to the Banffshire and Aberdeenshire coastlines some 60km south and south east of the application site. At these two locations the field data suggests an asymmetry in the tidal flow, where the current speeds are clearly greater when the tide is directed to the east during the flood. The model does not reproduce this asymmetry, although, the importance of these differences is reduced considering the distance from the application site to these locations. However, in the event that the cable route circumnavigates this zone its relevance must not be ignored.

The box and whisker plot in Figure 10 summarises the statistical analysis of the BODC field data and comparable model performance. While model mean current speeds are generally close to the field mean current speeds, it is noted that for a small number of locations the model exhibits a maximum speed 0.1m/s lower than the field records.

The tidal model is validated as being fit for purpose, providing a sufficiently realistic and accurate representation of the spatially and temporally varying tidal regime of the Moray Firth.

4.4 Bed Shear Stress Exceedance

In addition to the standard approach to calibration and validation of water levels and currents described above, consideration has also been given to the ability of the model to accurately predict tidally-induced bed shear stresses. Bed shear stress is the pressure applied to the sea bed by the tide that can mobilise sediment. Critical bed shear stresses are the bed shear stress thresholds at which sediments of various sizes become mobilised. Here, the model's ability to reproduce the durations for which the in-situ sediments are mobilised is assessed. For this purpose exceedance curves of bed shear stress are compared from the model with those determined empirically from the field data. Water depth and current speed are required for the calculation of bed shear stress using the methods outlined by Soulsby (1997). These calculations are summarised in Appendix A. The comparison of bed shear stress exceedance curves for the calibration period is provided in Figure 11.

The surficial bed sediments are understood to comprise predominately of glacial till containing sands, gravels and a low fraction of silt. These sediments are thought to remain immobile for the majority of tidal conditions, with the finer sand at the very surface being mobilised during storm events only. A comparison of bed shear stresses due to tides only derived from the model and field data is shown in Figure 11, demonstrates the ability of the model to reproduce characteristics of the bed shear occurrence at the deployment sites. Table 5 summarises the bed shear stress exceedance values for 300µm, 100µm and 64µm material. At both sites, the difference between model and field exceedances is less than ±1% for the three sediment sizes.

Table 5. Tide only bed shear stress exceedance for field and model: field (model)

Location	D50= 300µm (τcr = 0.20N/m²)		D50= 100µm (τcr = 0.14N/m²)		D50= 64µm (τcr = 0.12N/m²)	
	Exceedance (%)	Difference (%)	Exceedance (%)	Difference (%)	Exceedance (%)	Difference (%)
B2	0.07 (0)	-0.07	4.23 (4.12)	-0.10	6.82 (6.96)	0.14
B3	0 (0)	0	0.75 (0.50)	-0.25	2.74 (2.56)	-0.18

The differences between the model and field bed shear stress exceedance are small. Critical thresholds in the vicinity of the farm are met with enough accuracy to establish confidence in the model in respect to its reproduction of the processes which underlie the sediment transport regime.

5. Wave Model

5.1 General Design and Setup

The wave model uses the same model domain as the hydrodynamic model, with the addition of some extended boundaries. These extensions allow the relevant fetch lengths to be included in the wave calculations.

5.2 Wave Model Calibration

Combined wave measurements from the field have been recorded with a Triaxys wave buoy and two AWAC in early 2010. Calibration and validation of the wave model is undertaken in the same manner as the tidal model. Calibration was performed by simulating two periods from 15th February to 15th March and 15th September to 15th October 2010. Validation was undertaken by comparing the model's performance against the WaveNet data from the Moray Firth from the period 15h October to 15th November 2010

This is a particularly rigorous approach for wave model calibration and was made possible by the availability of suitable field data.

The level of calibration achieved by the wave model at the application site is shown in Figure 12 with a quantitative statistical assessment provided in Table 6.

Table 6. Wave model performance statistics for calibration comparison with the Beatrice Triaxys wavebuoy

Parameter	Significant Wave Height (m)		Peak Wave Period (s)		Wave Direction (°N) [from]	
	Field	Model	Field	Model	Field	Model
Mean	1.45	1.65	7.66	7.14	79.00	85.00
Mode	1.13	1.00	10.00	11.00	40.00	30.00
99 percentile	4.30	4.90	13.30	11.70	-	-

Figure 12 shows that the wave model is capable of reproducing events recorded in the field. Modelled peak significant wave heights are around 0.5m higher than those recorded in the field. Mean significant wave heights are around 0.2m higher than the field data. Modelled peak periods are generally within 1s and modelled mean wave directions are within 6° of the measured directions. These results demonstrate that the model is capable of reproducing well the wave climate of the region. Event timing can generally be considered excellent, as can the duration and persistence of events. Small differences in event timing lead to the greatest differences in the instantaneous wave heights, periods and directions. The resulting scatter in the direct correlations (Figure 13) of these parameters is therefore considered to be acceptable for the model's application to the determination of extreme wave conditions and scenario inter-comparisons.

5.3 Wave Model Validation

The validation achieved by the wave model at an independent site located some 30km to the south west of the application site (the WaveNet waverider buoy) is shown in Figure 13 with a quantitative statistical assessment provided in Table 7.

Table 7. Wave model performance statistics for validation comparison with the WaveNet Waverider buoy

Parameter	Significant Wave Height (m)		Peak Wave Period (s)		Wave Direction (°N) [from]	
	Field	Model	Field	Model	Field	Model
Mean	1.64	1.71	8.28	8.70	89.00	72.00
Mode	1.00	1.50	9.00	13.00	90.00	90.00
99 percentile	3.80	4.00	15.00	12.40	-	-

Figure 13 shows again that the wave model is capable of reproducing events recorded in the field at locations other than the application site itself. At the site of the WaveNet Waverider buoy the modelled peak significant wave heights are within 0.2m of the field recorded values while the mean climate is captured within 0.1m. Modelled mean peak periods are generally within 1s although it is noted that the modal peak period of the model differed from that of the field by 4s while the 99 percentile is 2.6s higher in the field than the model. This is due to the Waverider recording an isolated event with long periods which may or may not be real. Overall mean wave directions are within 17°, although the modal direction (categorised into 10° directional bins) match exactly. These overall correlations demonstrate that the model has a good capacity to reproduce the wave climate of the Moray Firth beyond the limits of the application site. Event timing can again be considered excellent as can the duration and persistence of events. As per model calibration, small differences in event timing lead to the greatest differences in the instantaneous wave heights, periods and directions. The resulting scatter in the direct correlations (Figure 15) of these parameters is therefore acceptable for the model's application to the determination of extreme wave conditions and scenario inter-comparisons.

The wave model is validated as being fit for purpose, providing a sufficiently realistic and accurate representation of the spatially and temporally varying wave climate of the Moray Firth.

6. Particle Tracking Model Setup

6.1 General Design and Setup

The particle tracking model is applied for the purposes of determining the fate of spoil material originating from the construction processes of drilling or dredging and possibly spoil disposal.

6.2 Calibration and Validation

The particle tracking model is based entirely upon the validated hydrodynamic model and does not have the same requirements for a verification process as the hydrodynamic or wave models. Additionally, there is a difficulty of collecting suitable field evidence against which to prove particle tracking models. However, the historical consistency of the model's performance underlines the suitability of applying the model in the north east European shelf sea region.

The model is controlled by three user-variable parameters:

- Longitudinal dispersion;
- Transversal dispersion; and
- Vertical dispersion.

The values applied in this model for these three parameters have been determined from the legacy of the model's use. Each value has proved suitable for model application for the sediment types and hydrodynamic regime found in the north east European self sea region around the UK. The applied values for these parameters are:

- Longitudinal dispersion: 15m²/s;
- Transversal dispersion: 0.5m²/s; and
- Vertical dispersion: 0.04m²/s.

The sediment types and corresponding characteristics are determined during the process of model application and are not considered as calibration factors. No further calibration is deemed necessary.

7. Conclusions, Notes on Model Application and Model Limitations

A numerical model of tides and waves has been constructed which includes Moray Firth and Smith Bank in detail. These models have been compared with data recorded *in-situ* at Smith Bank and throughout the Moray Firth. This comparison has shown that the numerical models are suitable to assist in the establishment of a conceptual understanding of physical processes of the region. In the context of the present study, tidal water levels and currents have been shown to be reproduced particularly well in the region of Smith Bank.

It must be noted that the tidal model along the Nairn Coast does not reproduce the asymmetry of the field data precisely. However, this assumes that the field data itself is truly representative of natural conditions. Here, field data indicate a net tidal flow to the east (out of the Firth). The strength of this asymmetry is not fully reproduced by the tidal model, although tidal current magnitudes are generally similar to those demonstrated in the field records. With this in mind, it is important that when the model is used to assess the feasibility of future scenarios appropriate consideration is given to the implications of any changes that may be indicated in the vicinity of the Nairn Coast. The cause of this difference was investigated but remains uncertain.

The best conceptual understanding of the Smith Bank sediment regime is built upon the available evidence from the field data, which represents a short-term snap-shot of the on-site conditions. It is not possible to directly measure the transport of sediments over Smith Bank and surrounding area, nor is it possible to prove the performance of a numerical model describing the sediment regime there from any data one might be able to capture from the field. As a result of this practical limitation, the characterisation of the sediment regime is restricted to the calculation of bed shear stresses, which are ultimately the driving force behind the sediment transport of any area. In this instance, the bed shear stresses calculated by the model are demonstrated to be comparable to those calculated from the field data. Therefore, a high level of confidence can be placed upon the use of the modelled bed shear stresses and their application to the determination of any implied changes to the local sediment regime. Additionally, the calculated bed shear stresses correspond generally with those expected from the conceptual understanding of the sediment regime, i.e. tidal bed shear stresses only exceed critical bed shear stresses for the in-situ sea bed sediments for peak tidal currents. This correlation enhances confidence in the conceptual understanding.

The wave model has been shown to reproduce well a representative wave climate in the vicinity of the application site when compared to the *in-situ* field data. The field data captures a number of large wave events which are reproduced by the model. This gives confidence to the model's performance throughout the range of likely conditions incident upon the application site and the Moray Firth.

The quality of the particle tracking model is rooted in the performance of the underlying tidal model, which has proven to perform well. The application of the particle tracking model is limited to a small extent by its grid resolution. Each application of the particle tracking model tends to require long model runs which generate large results files. The size of these files must be controlled to some degree by lowering the level of detail in the model grid as distance from the areas of interest increases. Lower grid resolutions applied at distance from the areas of interest result in reduced accuracy in the calculation of suspended sediment concentrations and bed deposition thickness. However, the spatial extents over which sediments are dispersed are independent of the absolute grid resolution and remain dependent upon the quality of the underlying tidal model.

8. References

ABPmer, 2011. Numerical model calibration and validation guidance. R.1400/112 (internal research report).

COWRIE, 2009. Coastal Process Modelling for Offshore Wind farm Environmental Impact Assessment: Best Practice Guide. ABPmer & HR Wallingford for COWRIE, 2009, http://www.offshorewindfarms.co.uk

ETSU, 2002. Potential Effects of Offshore Wind Developments on Coastal Processes. Report Ref. W/35/00596/00/REP.

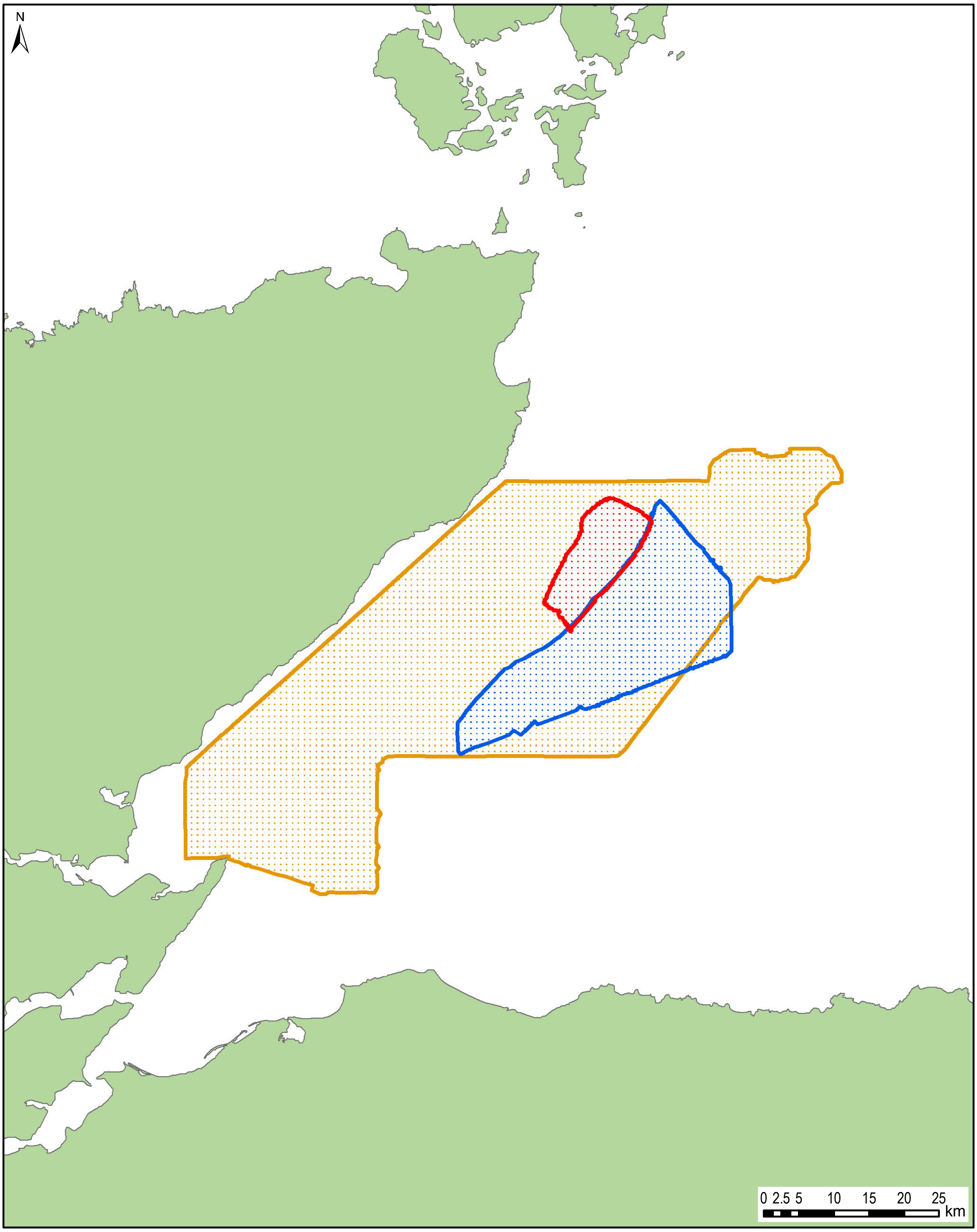
Soulsby, R. L., 1997. Book: Dynamics of Marine Sands. Thomas Telford Publications. 249 pages.

9. Abbreviations

%	Percent(age)
µ	Micron(s)
2D	Two-Dimension(al)
3D	Three-Dimension(al)
ABPmer	ABP Marine Environmental Research Ltd
AWAC	Acoustic Wave And Current profiler
BODC	British Oceanographic Data Centre
COWRIE	Collaborative Offshore Wind Research Into The Environment
DHI	Danish Hydraulic Institute
Dir	Direction
Etopo2	Earth TOPOgraphy database, global digital elevation data administered by NOAA/NGDC,
ETSU	Energy Technology Support Unit
GIS	Geographic information system
Hs	Significant Wave Height
km	Kilometre(s)
KMS	Tidal constituent model,
m	Metre(s)
MCA	Maritime and Coastguard Agency
MIKE21FM	MIKE21 Flexible Mesh, marine software by DHI
mins	Minute(s)
n/a	Not Applicable
N/m²	Newtons Per Square Meter
NCEP	National Centers for Environmental Prediction
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
°	Degree(s)
Osiris	Osiris Hydrographic & Geophysical Projects Ltd

Partrac	Partrac Ltd
s	Second(s)
τcr	Critical bed shear stress
Tp	Peak wave period
UK	United Kingdom
Vs	versus
WL	Water Level

Figures



Date	By	Size	Version
Oct 11	NKD	A4	1
Projection		WGS84 UTM30N	
Scale		1:800,000	
QA		MV	
3888_009_Fig1_Swathbathy_extents			
Produced by ABPmer Ltd			

NOT TO BE USED FOR NAVIGATION

BOWL swath bathymetry coverage

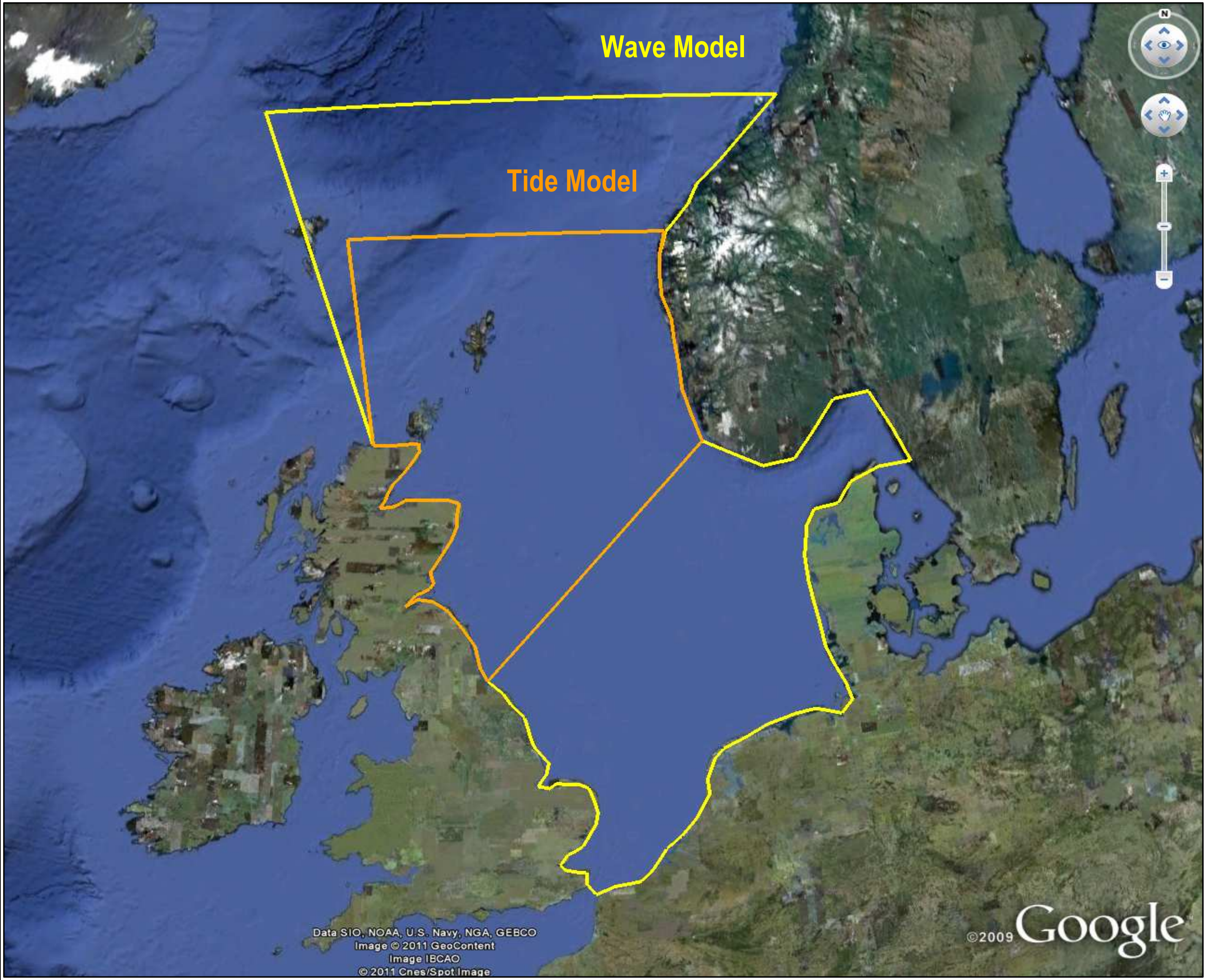
MORL swath bathymetry coverage

MCA swath bathymetry coverage

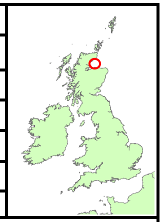
ABP mer marine environmental research

Swath Bathymetry Coverage in the Moray Firth

Figure 1



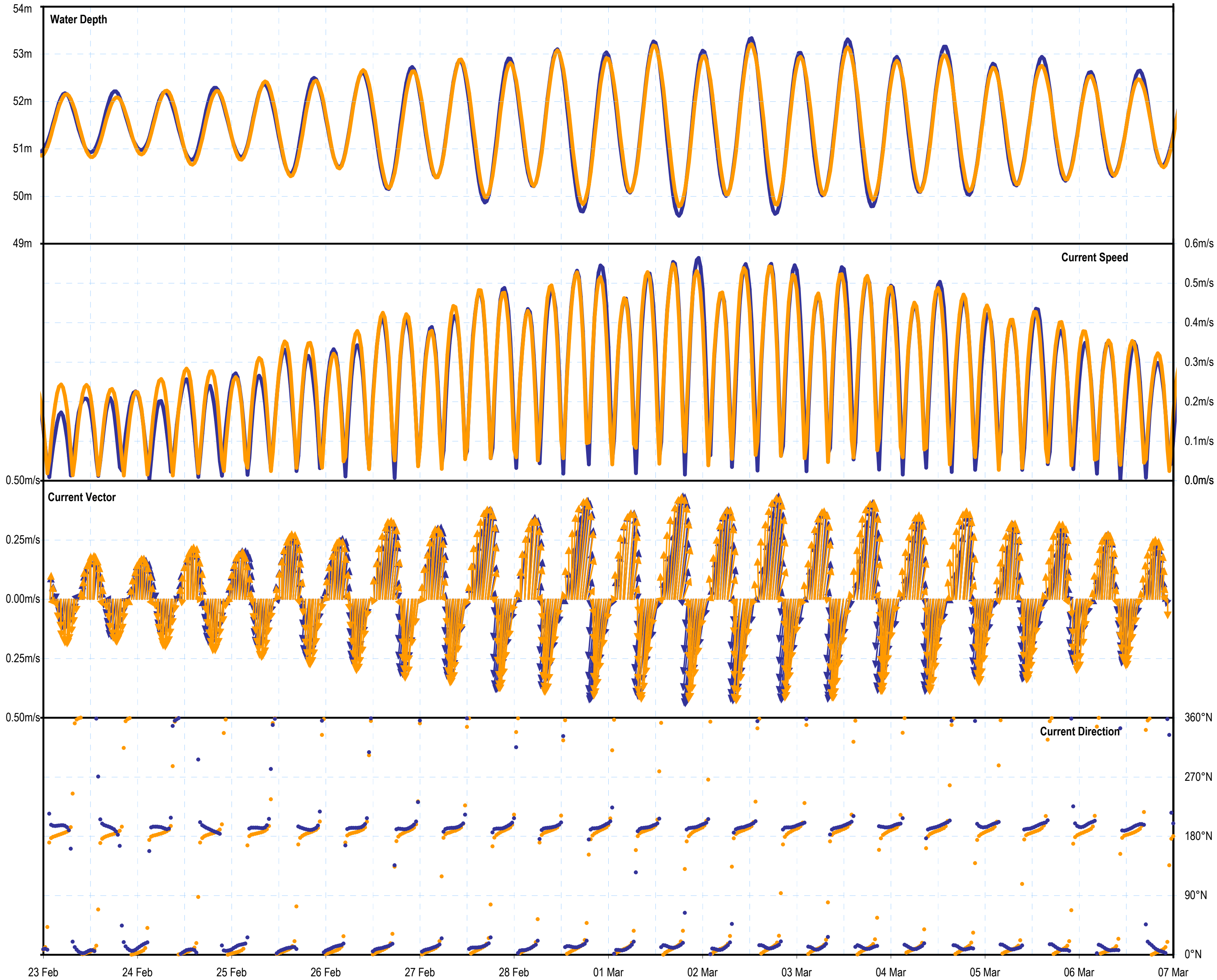
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



ABP mer
marine environmental research

Model Domain Extents

Figure 2



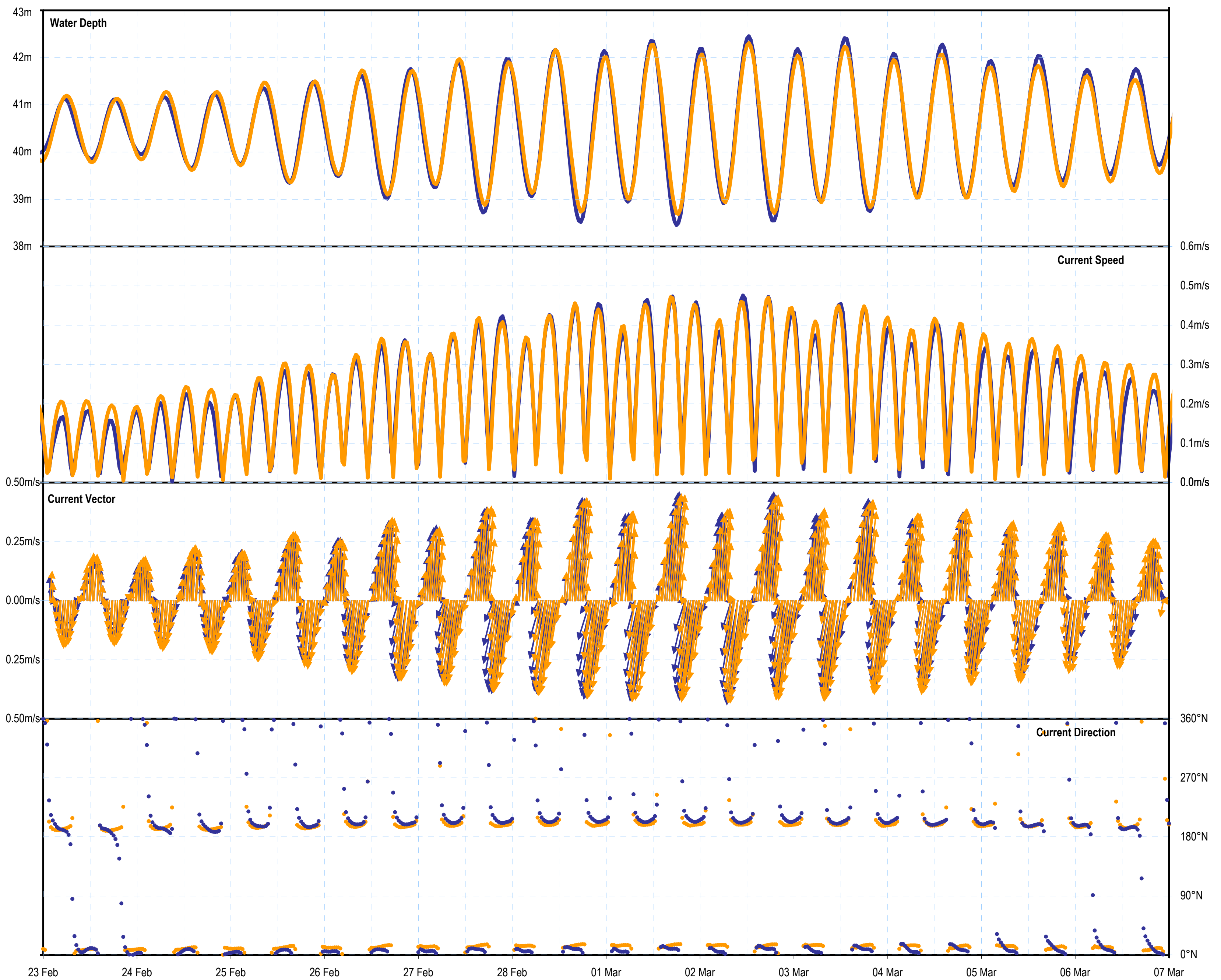
Field series are blue
Model series are orange

Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

ABP mer
marine environmental research

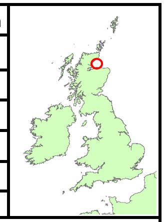
Comparison of Model Tides with B2a Field Records

Figure 3



Field series are blue
Model series are orange

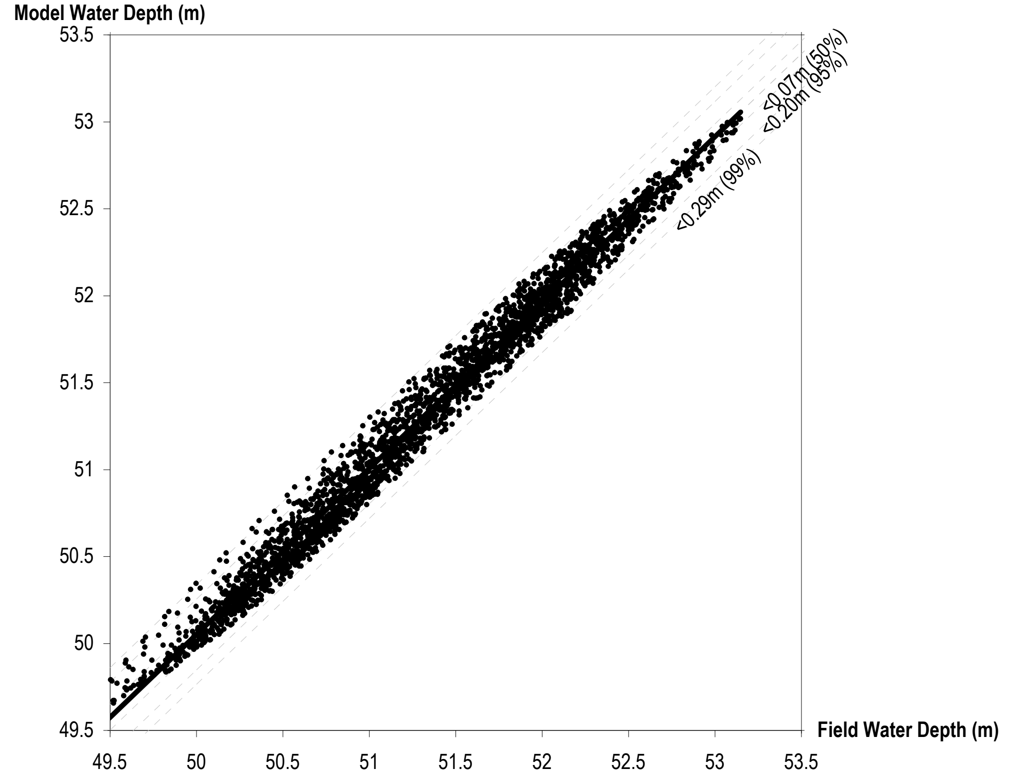
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

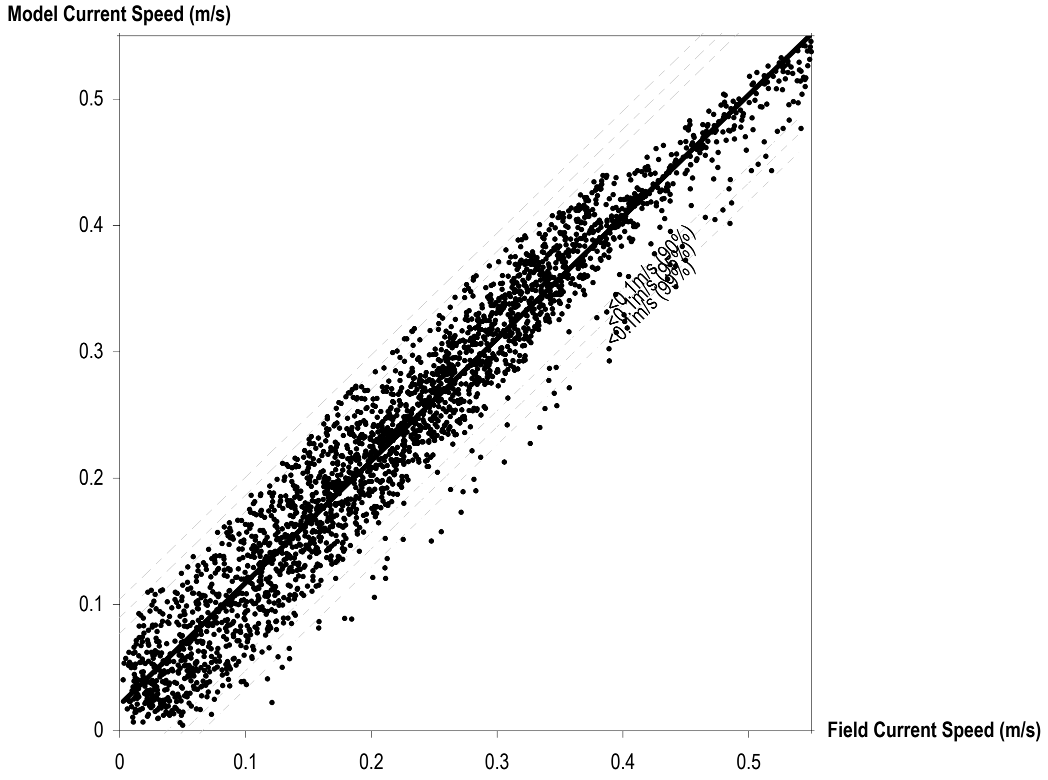


ABP mer
marine environmental research

Comparison of Model Tides with B3a Field Records

Figure 4



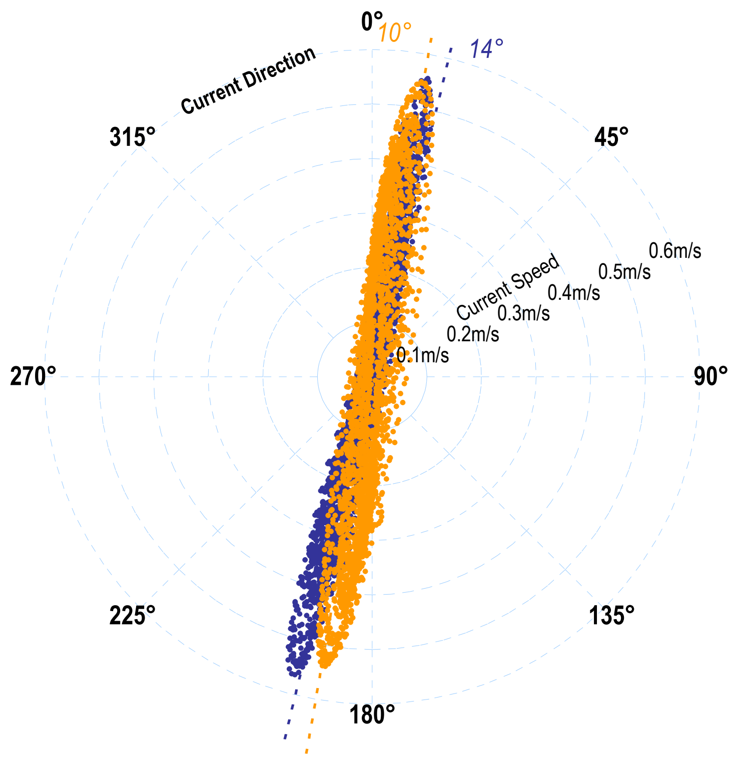


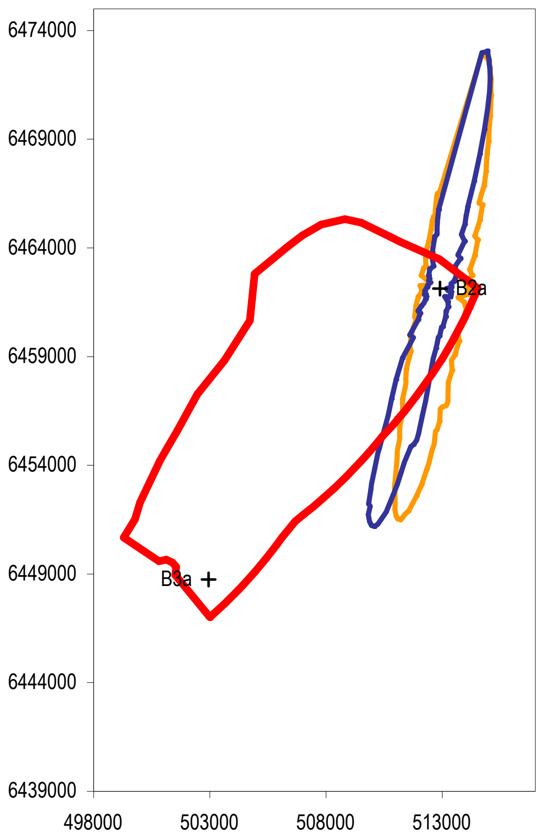
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

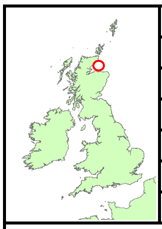
ABP mer marine environmental research

Comparison of Model and Field (B2a) Tidal Water Level and Current Speed Performance

Figure 5







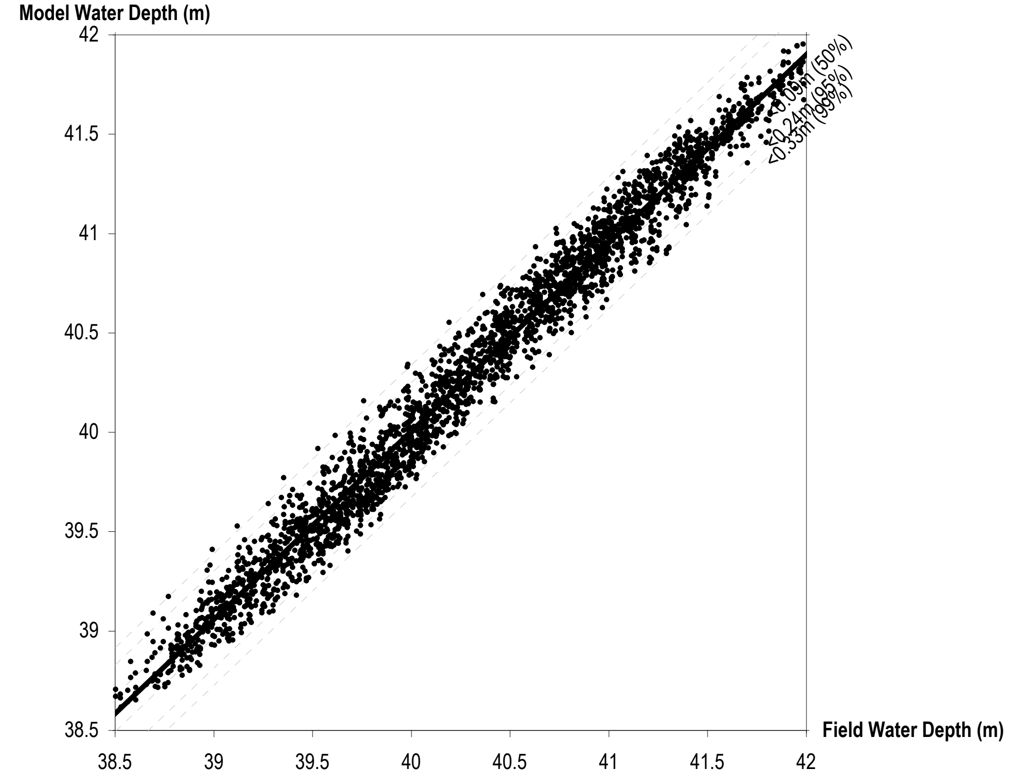
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

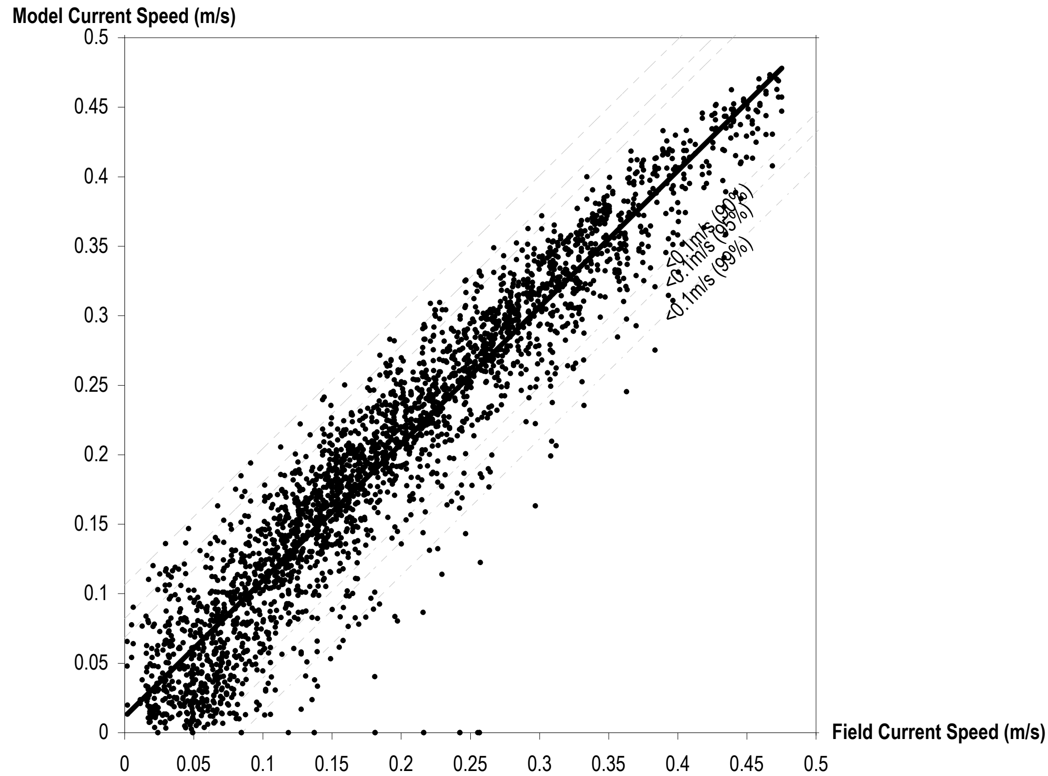
Field series are blue
Model series are orange

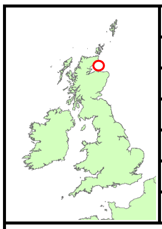
ABP mer marine environmental research

Comparison of Model and Field (B2a) Tidal Current Direction Performance

Figure 6





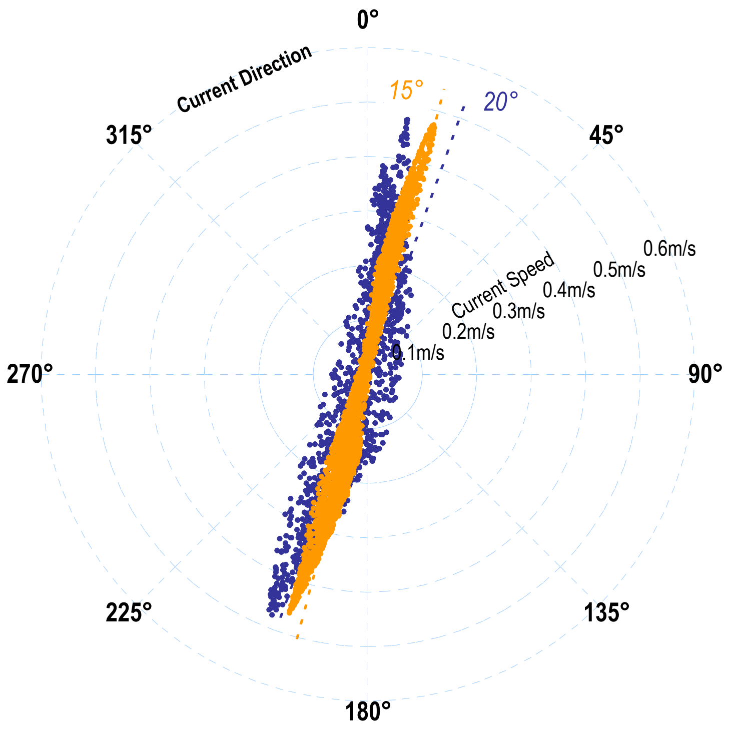


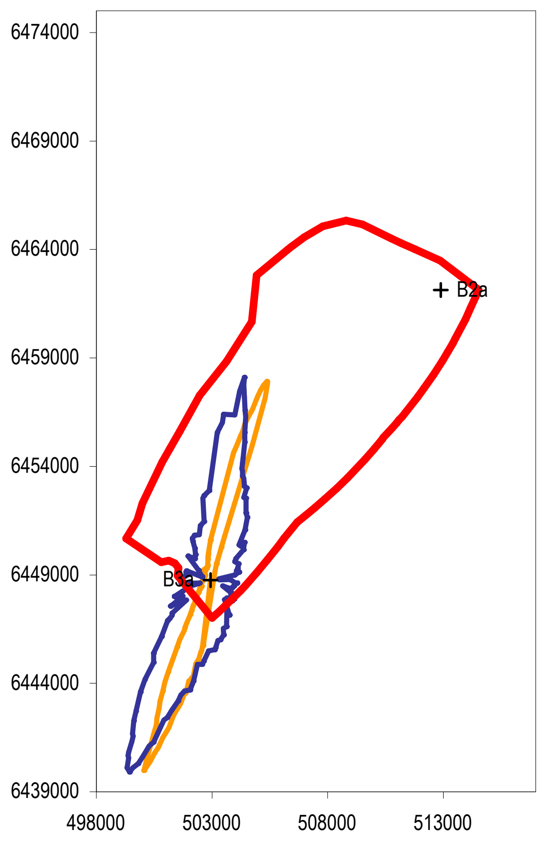
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

ABP mer marine environmental research

Comparison of Model and Field (B3a) Tidal Water Level and Current Speed Performance

Figure 7





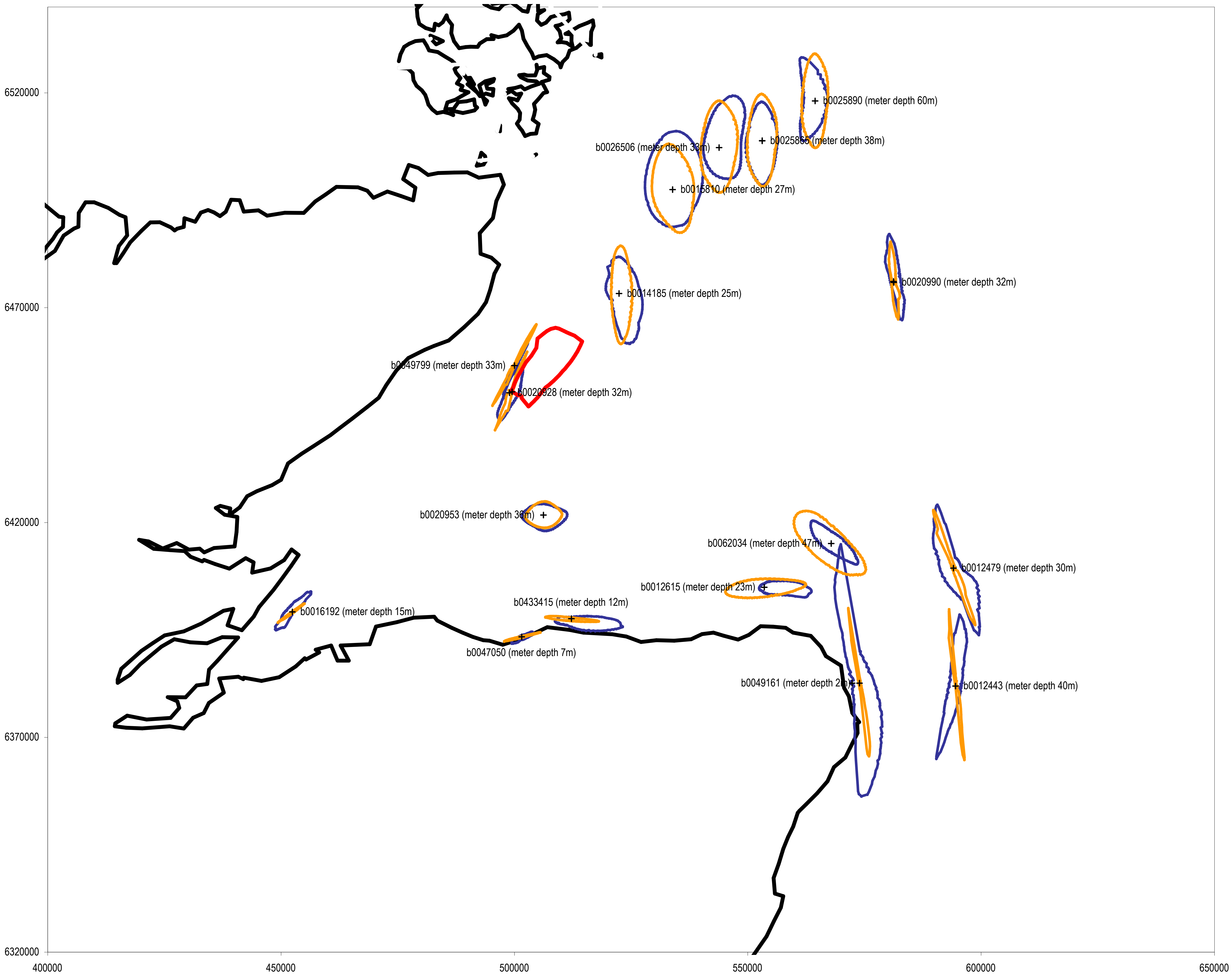
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

Field series are blue
Model series are orange

ABP mer marine environmental research

Comparison of Model and Field (B3a) Tidal Current Direction Performance

Figure 8

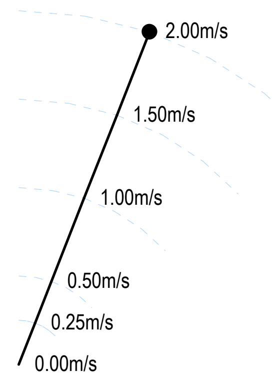


Field envelopes are blue
Model envelopes are orange

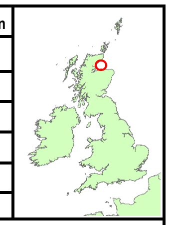
Field data are at specific quoted depths below the surface

Field data are harmonic (meteorology has been removed)

Model data are depth average



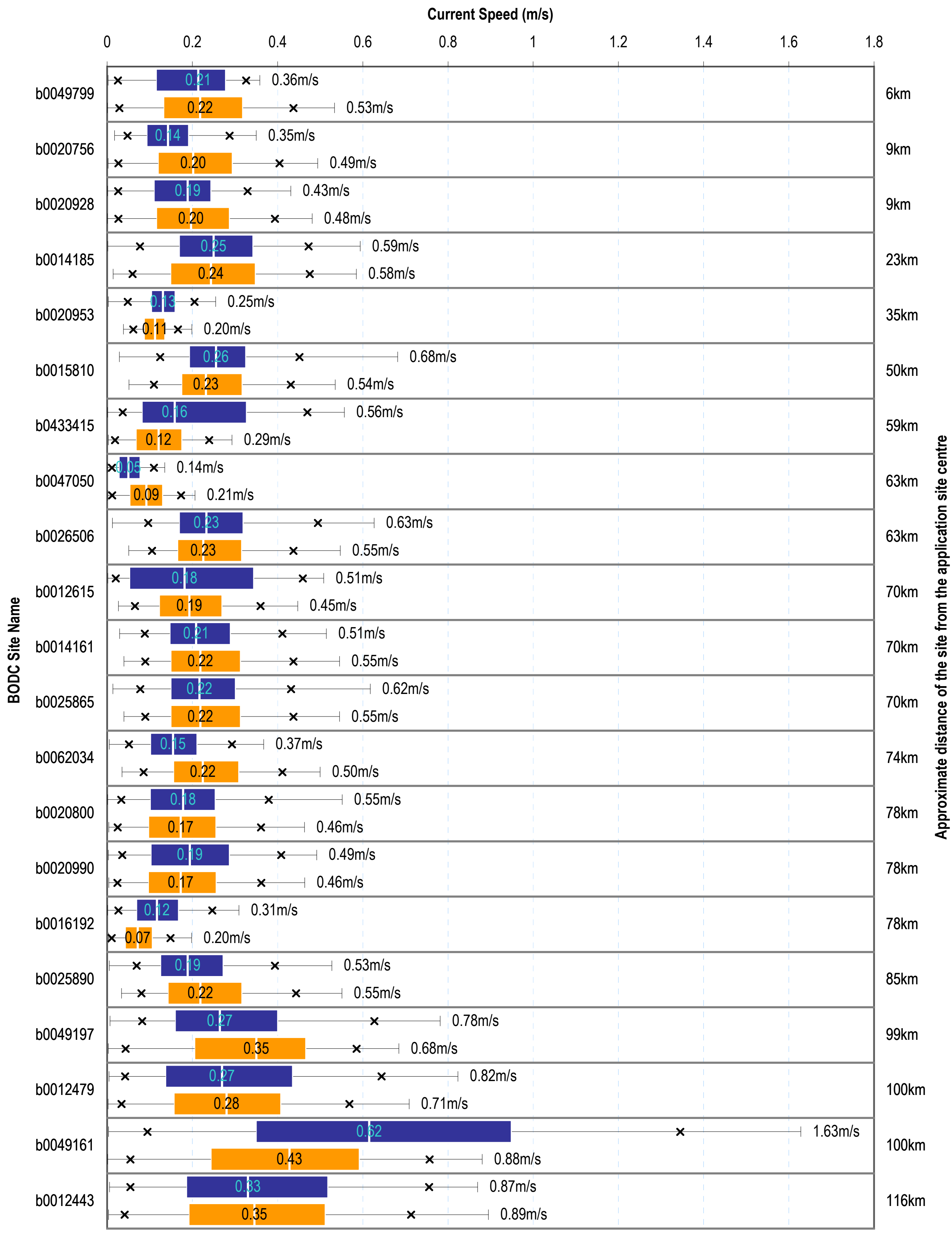
Date	By	Size	Version
Dec '11	NW	A3	1
Projection	UTM30		
Scale	n/a		
QA	JJW		
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



ABP mer marine environmental research

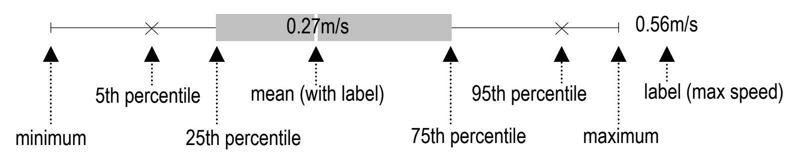
Tidal Current Speed Envelope Comparison (Model vs BODC Current Meters)

Figure 9



Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

Box and Whisker nomenclature:



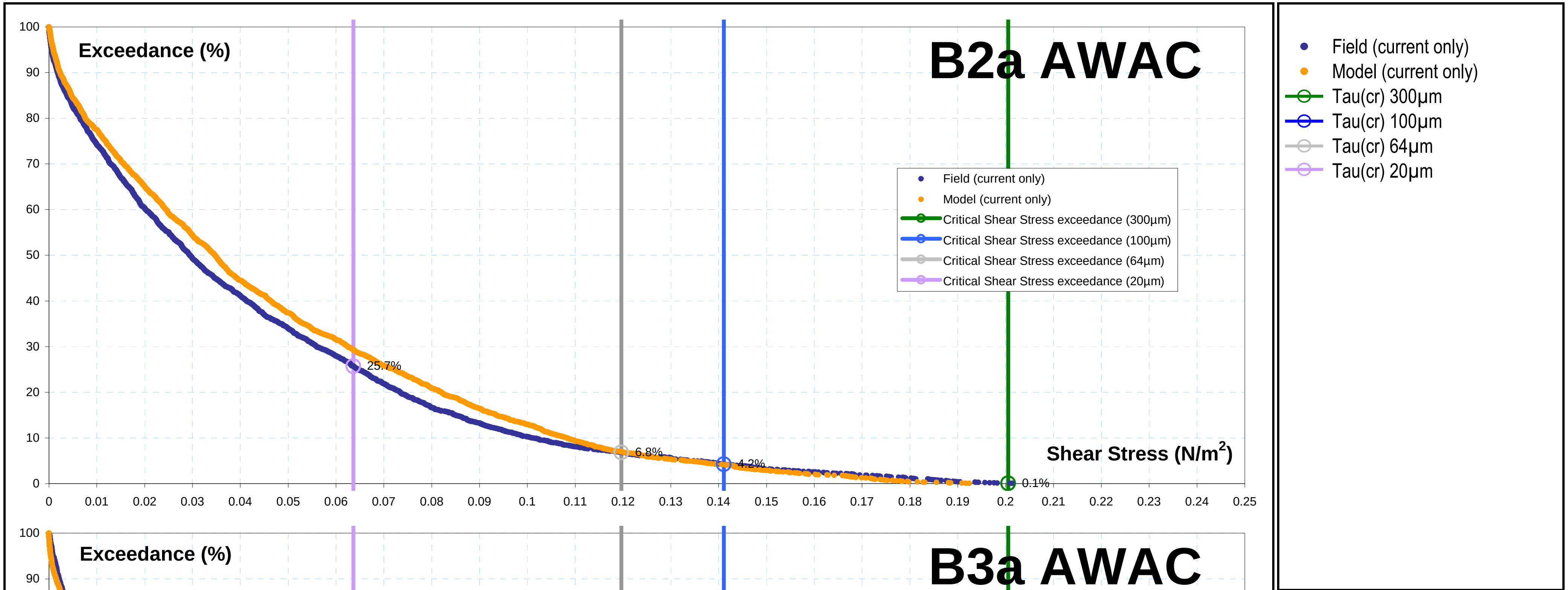
Field data are blue

Model data are orange

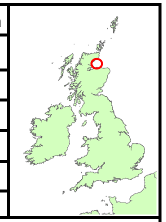
ABP mer
marine environmental research

Tidal Current Speed Statistical Comparison (Model vs BODC Current Meters)

Figure 10



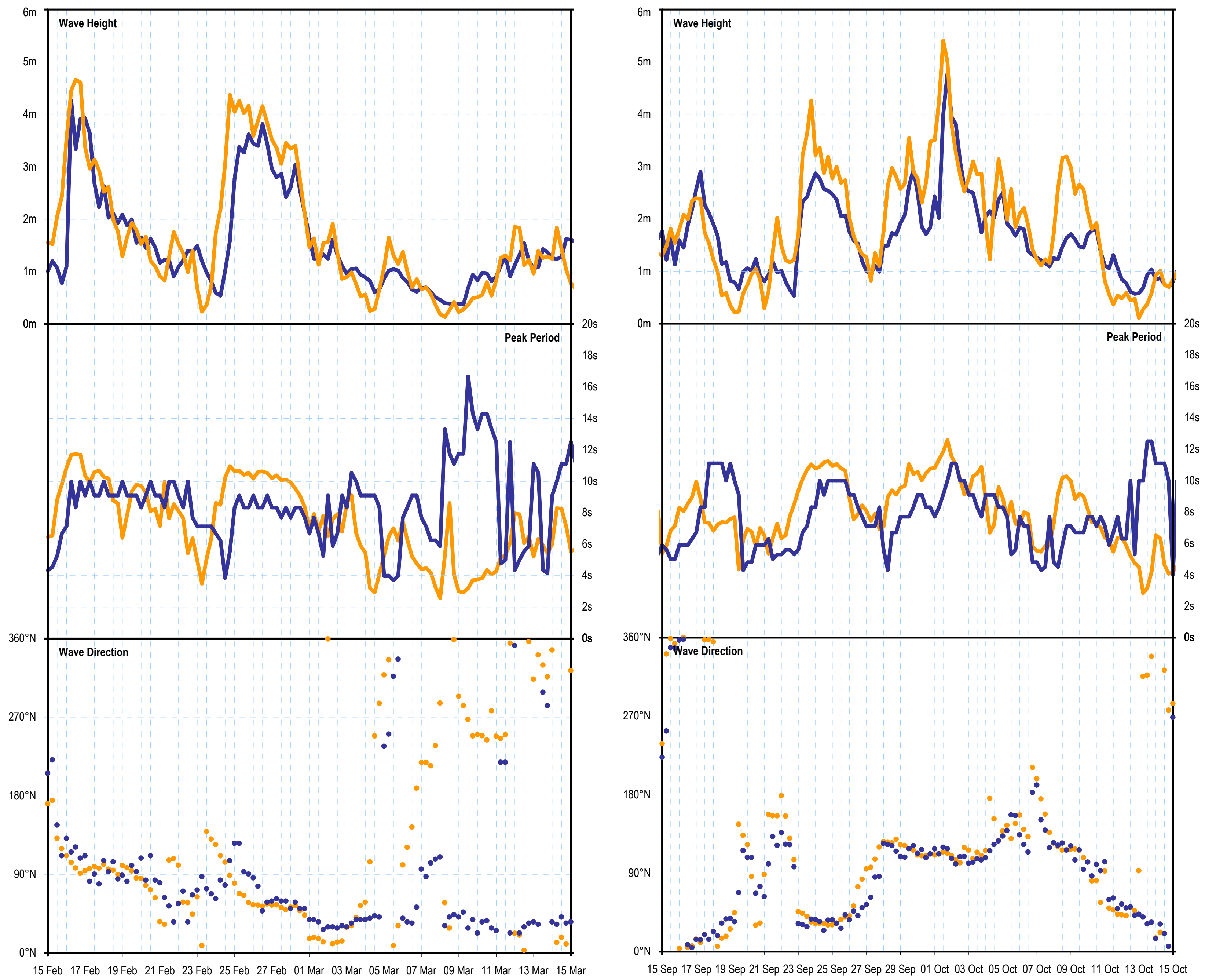
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



ABP mer marine environmental research

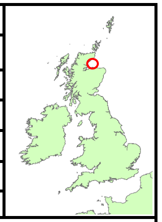
Comparison of Field and Model Bed Shear Stress Exceedance (Tide Only)

Figure 11



Field series are blue
Model series are orange

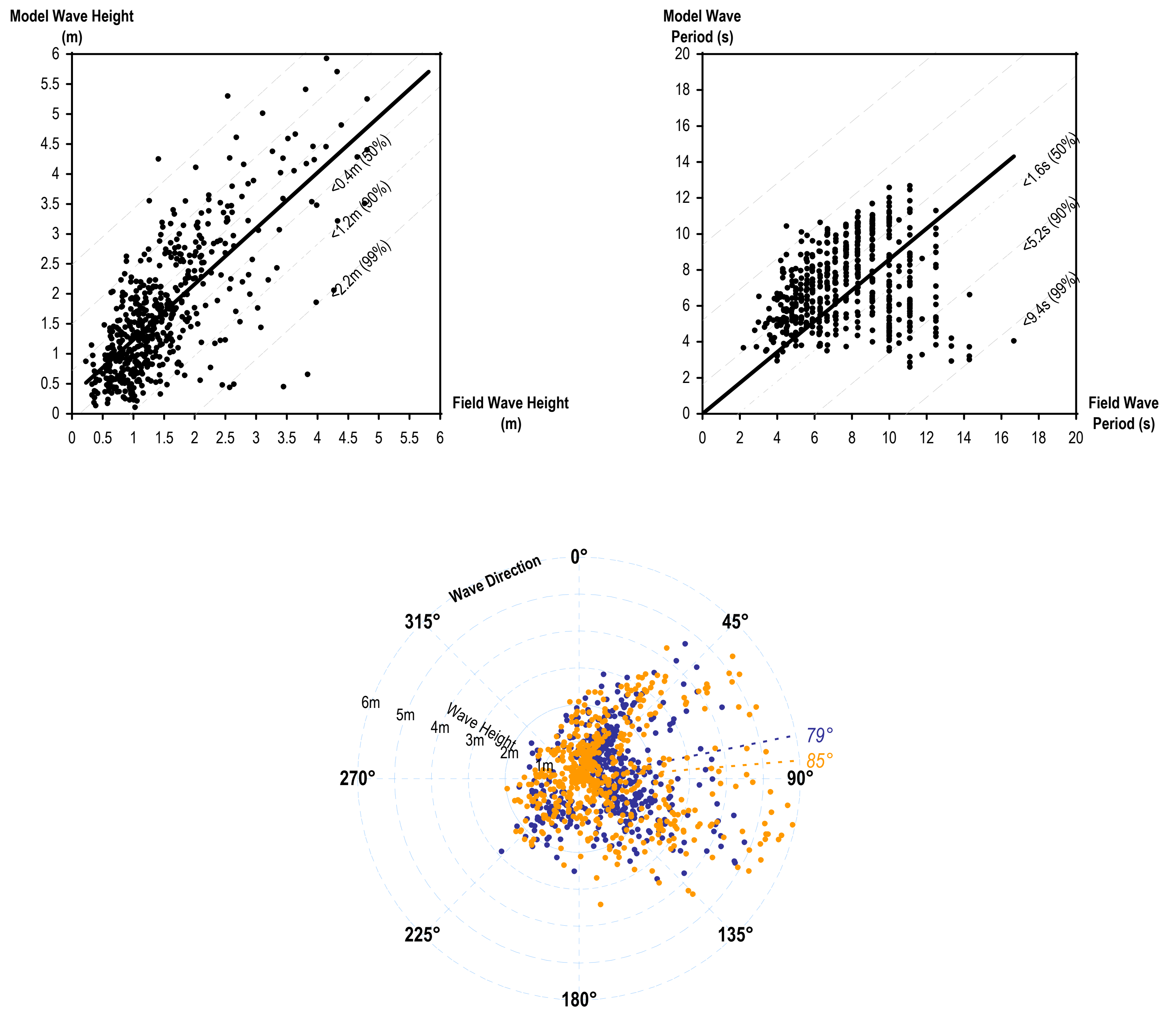
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



marine environmental research

Comparison of Model Wave Timeseries Parameters with Waverider Field Data

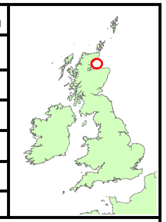
Figure 12



Field series are blue

Model series are orange

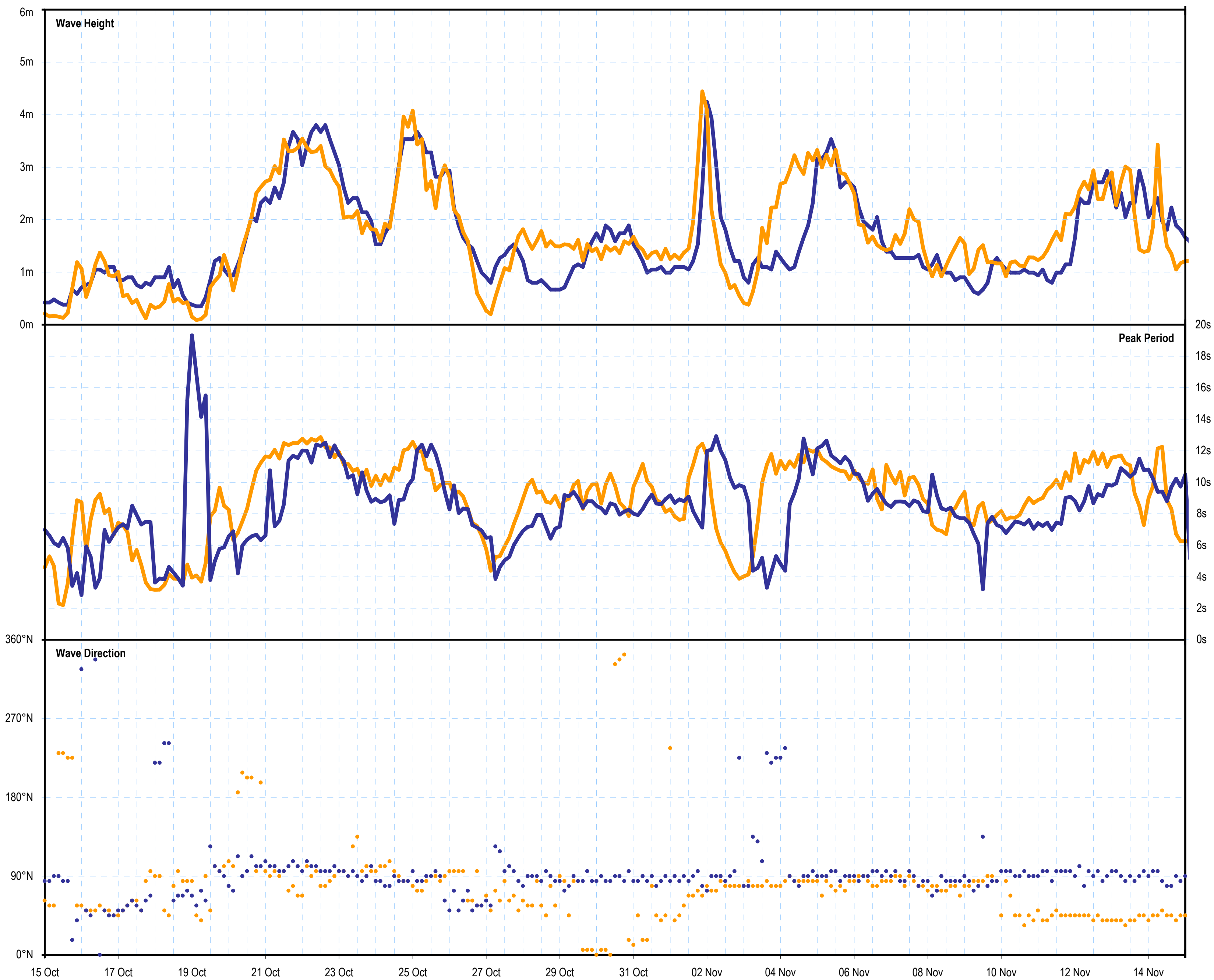
Date	By	Size	Version
Dec '11	NW	A4	1
Projection	n/a		
Scale	n/a		
QA	JJW		
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



ABP mer
marine environmental research

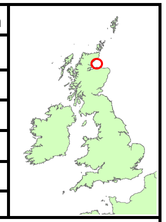
Comparison of Model and Waverider Field Wave Parameter Performance

Figure 13



Field series are blue
Model series are orange

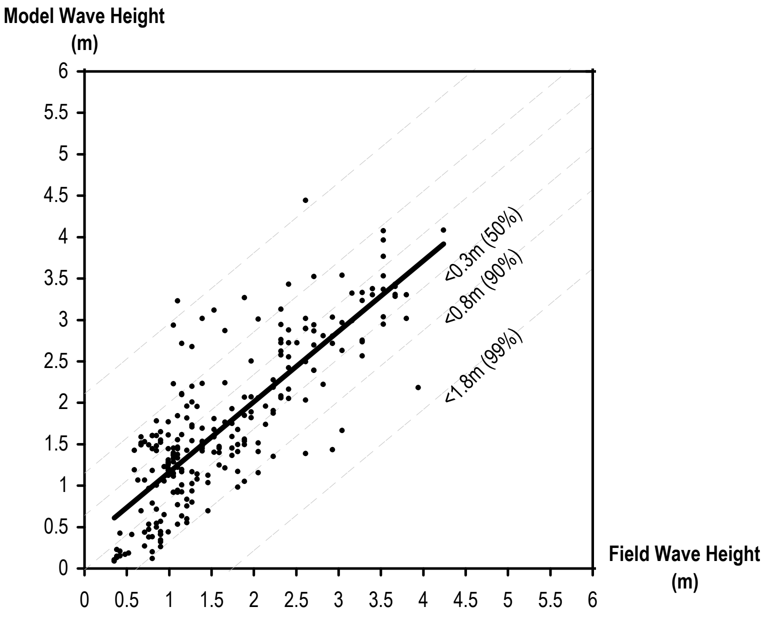
Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			

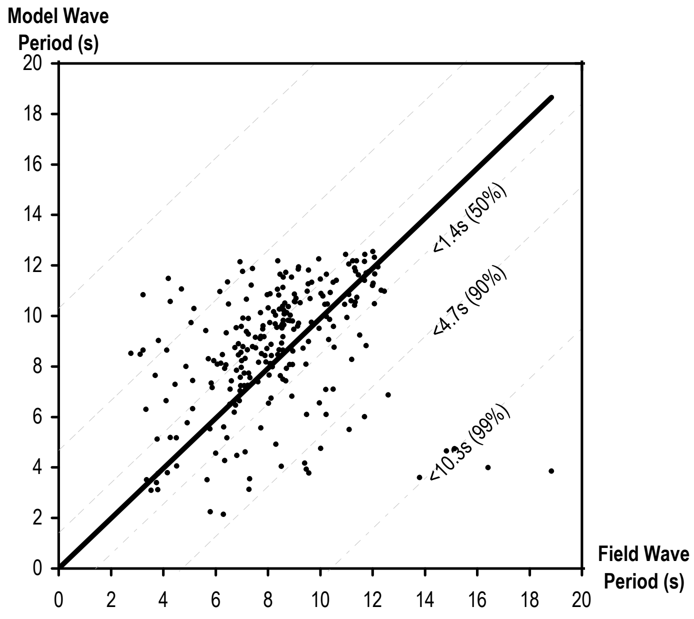


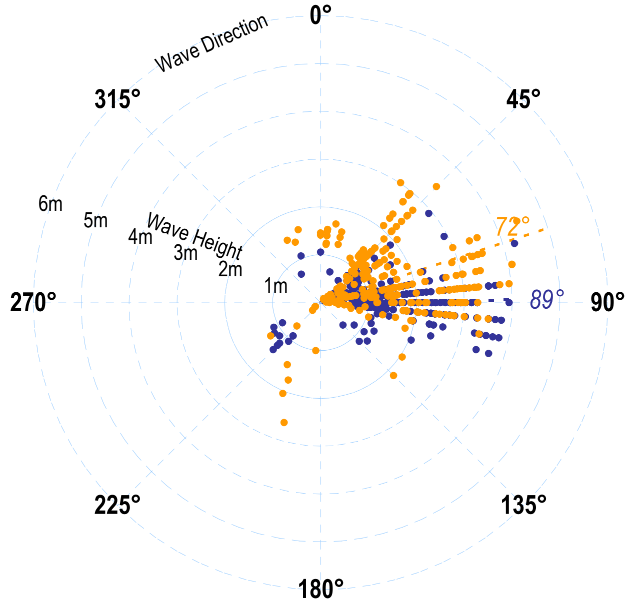
ABP mer
marine environmental research

Comparison of Model Wave Timeseries Parameters with WaveNet Field Data

Figure 14



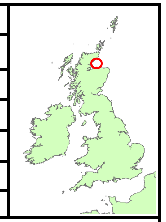




Field series are blue

Model series are orange

Date	By	Size	Version
Dec '11	NW	A4	1
Projection		n/a	
Scale		n/a	
QA		JJW	
3888_Model-calib-figs.xls			
Produced by ABPmer Ltd.			



ABP mer marine environmental research

Comparison of Model and WaveNet Field Wave Parameter Performance

Figure 15

Appendices

Appendix A

Bed Shear Stress Calculation

Appendix A. Bed Shear Stress Calculation

Benthic surveys of the application site and surroundings have provided the data with which to characterise the surficial sea bed sediments in terms of their size and type. With this knowledge of the sediments and the measured flow data it is possible to calculate the bed shear stresses that the tidal flows exert upon the sea bed. The bed shear stresses can be placed within context by comparing them to the critical bed shear stresses at which the in-situ sediments begin to become mobile. Understanding the frequency and persistence of occasions when the various in-situ sediments are mobile enhances the understanding upon which the conceptual model of the regional sediment regime is based.

Bed shear stress is defined as a function of the density of sea water and the friction velocity: The friction velocity is dependent upon a representative grain size, the current speed and the water depth. These relationships are defined by the formulae of Soulsby (1997)and are detailed below. These formulas are adapted for use as in-house tools that are used regularly and widely throughout ABPmer.

$$\tau_{current} = \rho u_*^{\,2} \qquad \text{Eq.A}$$

$$\frac{u_*}{U} = \frac{1}{7}\left(\frac{d_{50}}{h}\right)^{\frac{1}{7}} \qquad \text{Eq.B}$$

Where:

$\tau_{current}$ = bed shear stress due to currents

ρ = density of sea water

u_* = friction velocity

d_{50} = median sediment grain size

U = current speed

It should be noted that the thresholds considered are for unmixed sediments of a single grain size, and that mixed sediments, such as those on site, may experience consolidation and not exhibit a threshold of movement equivalent to its component sediment grain sizes.

ABP Marine Environmental Research Ltd (ABPmer)
Suite B, Waterside House, Town Quay, Southampton, Hampshire SO14 2AQ

T +44 (0)23 8071 1840
F +44 (0)23 8071 1841
E enquiries@abpmer.co.uk

www.abpmer.co.uk

Creating sustainable solutions for the marine environment